Vector boson plus multijet production
IPPP/13/07, DCPT/13/14, LPN13-019

Marek Schönherr

Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, UK

E-mail: `marek.schoenherr@durham.ac.uk`

Abstract. In this contribution the developments in the description of vector boson plus jets signatures at hadron colliders in recent years are summarised. Particular focus is put on its relevance as background to top physics.

1. Introduction
Within the first years of running of the LHC at centre-of-mass energies of 7 and 8 TeV top physics has been at the core of its physics programme. It serves both as a signal to be measured as precisely as possible and as a background to new physics, Higgs and Standard Model processes with many jets.

When considering measuring top quark production the production of W and Z bosons in association with many jets present the major backgrounds. In particular, the process $pp \to W+ \geq 4$ jets constitutes an irreducible background to the semileptonic $t\bar{t}$ production channel. It therefore needs to be known with as large a precision as possible. Many advances have been made in recent years for this class of processes in their own right, reaching now a stage where they start to decrease the theoretical uncertainties for the relevant background channels below the leading order.

While higher order calculations for $V(= W, Z)$ plus multiple jets become accessible they improve the description of QCD at large scales, leading to a stabilisation of the respective cross sections at the same time. But only when they are matched to parton showers a simultaneous and observable independent, reliable description of QCD dynamics at low scales is achieved. Such a matching offers additional benefits as the connection of low scale perturbative dynamics of the parton shower to the non-perturbative dynamics of hadronisation models and their subsequent hadron decays can be used to arrive at particle level descriptions that are directly comparable to experimental data. Multijet merging techniques can then be evoked to arrive at inclusive descriptions, combining successive multiplicities of fixed-order matrix elements matched to parton showers with their respective accuracies preserved and, at the same time, resumming multiscale logarithm associated with hierarchical multijet production.

2. LO calculations and MEPS merging
Multijet merging techniques at leading order accuracy are known for more than ten years [1, 2, 3, 4, 5, 6, 7, 8, 9]. Combining tree-level matrix elements of successive parton multiplicities with parton showers into an inclusive description, preserving the respective accuracies, they are by now the work horses of the LHC experiments for multijet topologies. Their ability to describe data has been tested in various analyses [10, 11, 12, 13, 14].
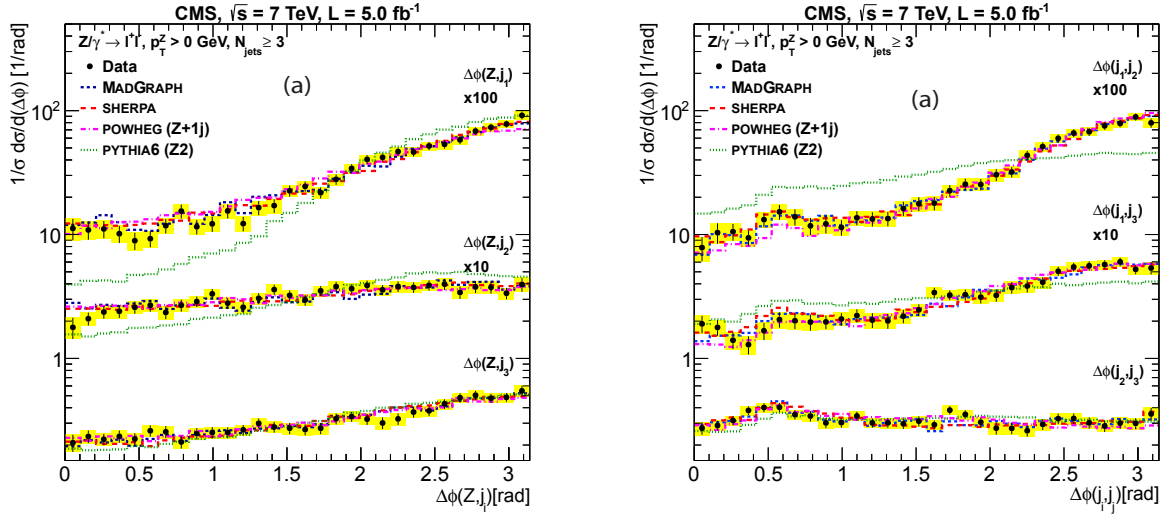
Figure 1: Azimuthal decorrelation of the Z and the 1st, 2nd and 3rd jet **(left)** and of the 1st and 2nd, 1st and 3rd, and 2nd and 3rd jet in $pp \rightarrow Z+ \geq 3$ jets at the LHC as measured by CMS. Figures are taken from [14].

Fig. 1 presents the most recent of these analyses wherein the ability of the MEPs methods to describe the radiation pattern of the jets in $pp \rightarrow Z+ \geq 3$ jets events is examined and good agreement is found. Nonetheless, the theoretical uncertainties of these methods are large owing to the leading order accuracy of the description of hard and/or wide angle parton emission, including quantum interference effects, only. By elevating their description to next-to-leading order the theoretical uncertainties on the respective observables can be reduced.

3. NLO calculations, NloPs and MePs@Nlo

NLO

While next-to-leading order calculations for W and Z production with up to two jets are known for some time [15], such calculation for $pp \rightarrow W + 3$ jets [16, 17] and $pp \rightarrow W + 4$ jets [18], as are relevant as top backgrounds, have only become available recently. Similarly, $pp \rightarrow Z + 3$ jets [19] and $pp \rightarrow Z + 4$ jets [20] are available.

Fig. 2 shows a calculation of the transverse momenta of four leading jets in $pp \rightarrow W + 4$ jets production at the LHC using BLACKHAT+SHERPA [18, 21] and a clear reduction of the theoretical uncertainty can be seen. However, possibly large logarithms due to scale hierarchies are not taken into account by such a calculation and also small scale dynamics are absent.

NLoPs

To enhance next-to-leading order calculations with the resummation of large logarithms associated with the production of the softest jet it can be matched to a parton shower, either via the MC@NLO [22, 23, 24] or the POWHEG [25, 26, 27, 28] technique. Such a calculation has the added benefit that it can take advantage of the parton shower's infrared continuation with the non-perturbative dynamics of hadronisation models with subsequent hadron decays, and multiple parton interactions. Thus, such calculation can directly be compared to experimental data.

Fig. 3 shows the results of implementations of these methods by various groups, reaching up to multiplicities of $pp \rightarrow V + 3$ jets described at NLO. For all, good agreement with data is
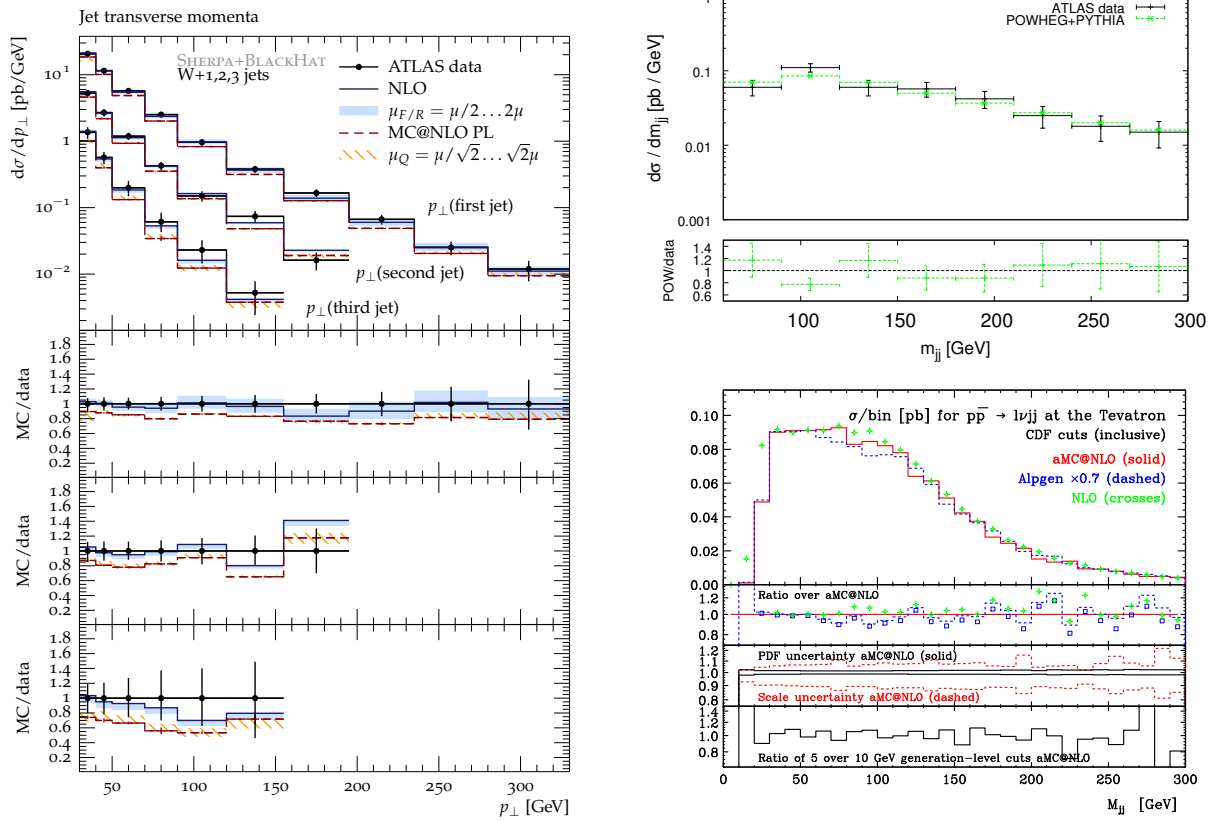
Figure 2: Transverse momenta of the four leading jets in $pp \rightarrow W^- + 4$ jets at the LHC calculated at NLO accuracy. Figures taken from [18].

found and the respective uncertainties are reduced compared to LO calculations.

MEPS@NLO

NLOPS calculations, like fixed-order NLO calculations, are lacking any resummation, of scale hierarchies of jet emissions that are described at NLO accuracy, e.g. of the emission scales of the four leading jets in $pp \rightarrow V + 4$ jets. Such a resummation of scales with respect to the inclusive sample, however, are present in MEPS methods. Therefore, as a first step, NLOPS calculations were combined with MEPS merging methods to the called MENLOPS merging method [32, 33]. Therein the most inclusive process is described by a NLOPS matched calculation while leading order matrix elements are merged on top of it.

MEPS@NLO merging [34, 35, 36] now aims at merging NLOPS matched calculations of successive jet multiplicities into such an inclusive sample. Therein, not only are the respective jet multiplicities described at next-to-leading order accuracy, but also the overall resummation of the parton shower is undisturbed. Thus, both large and small scale dynamics are accurately described.

Fig. 4 displays the inclusive n-jet cross sections and the azimuthal decorrelation of the two leading jets, probing both relative production rates and interjet dynamics. Comparing the uncertainties of the MEPS@NLO merging method (merging $pp \rightarrow W + 0, 1, 2$ jets at NLO and $pp \rightarrow W + 3, 4$ jets at LO) to those of the MENLOPS method (merging $pp \rightarrow W + 0$ jets at NLO and $pp \rightarrow W + 1, 2, 3, 4$ jets at LO) one clearly seas the added precision of including more NLO matrix elements. The predictions are compared to ATLAS data [11] and also the more accurate method is favoured. Fig. 5 presents the transverse momenta of the two leading jets in events with at least one, two or three jets. A similar reduction of the uncertainties is found.

Finally, with these methods at hand, a full assertion of all perturbative and non-perturbative uncertainties in particle level Monte-Carlo predictions following [37] can be done.

Figure 3: Left: Transverse momenta of the nth jet in MC@NLO simulations of $pp \to W + n$ jets at the LHC compared to ATLAS data [11]. **Right top:** Invariant mass of the leading jet pair in a POWHEG simulation of $pp \to Z + 2$ jets at the LHC compared to ATLAS data [12]. **Right bottom:** Invariant mass of the leading jet pair in a aMC@NLO simulation of $p\bar{p} \to W + 2$ jets at the Tevatron. Figures taken from [29, 30, 31]

References

[1] Catani S, Krauss F, Kuhn R and Webber B R 2001 *JHEP* **11** 063 (*Preprint* hep-ph/0109231) URL http://www.slac.stanford.edu/spires/find/hep/www?eprint=hep-ph/0109231

[2] Mangano M L, Moretti M and Pittau R 2002 *Nucl. Phys.* **B632** 343–362 (*Preprint* hep-ph/0108069) URL http://www.slac.stanford.edu/spires/find/hep/www?eprint=hep-ph/0108069

[3] Lönnblad L 2002 *JHEP* **05** 046 (*Preprint* hep-ph/0112284) URL http://www.slac.stanford.edu/spires/find/hep/www?eprint=hep-ph/0112284

[4] Krauss F 2002 *JHEP* **0208** 015 (*Preprint* hep-ph/0205283) URL http://www.slac.stanford.edu/spires/find/hep/www?eprint=hep-ph/0205283

[5] Mangano M L, Moretti M, Piccinini F and Treccani M 2007 *JHEP* **01** 013 (*Preprint* hep-ph/0611129) URL http://www.slac.stanford.edu/spires/find/hep/www?eprint=hep-ph/0611129

[6] Alwall J *et al.* 2008 *Eur. Phys. J.* **C53** 473–500 (*Preprint* 0706.2569) URL http://www.slac.stanford.edu/spires/find/hep/www?eprint=arXiv:0706.2569

[7] Höche S, Krauss F, Schumann S and Siegert F 2009 *JHEP* **05** 053 (*Preprint* 0903.1219) URL http://www.slac.stanford.edu/spires/find/hep/www?eprint=arXiv:0903.1219

[8] Hamilton K, Richardson P and Tully J 2009 *JHEP* **11** 038 (*Preprint* 0905.3072) URL http://www.slac.stanford.edu/spires/find/hep/www?eprint=arXiv:0905.3072

[9] Lönnblad L and Prestel S 2012 *JHEP* **03** 019 (*Preprint* 1109.4829)

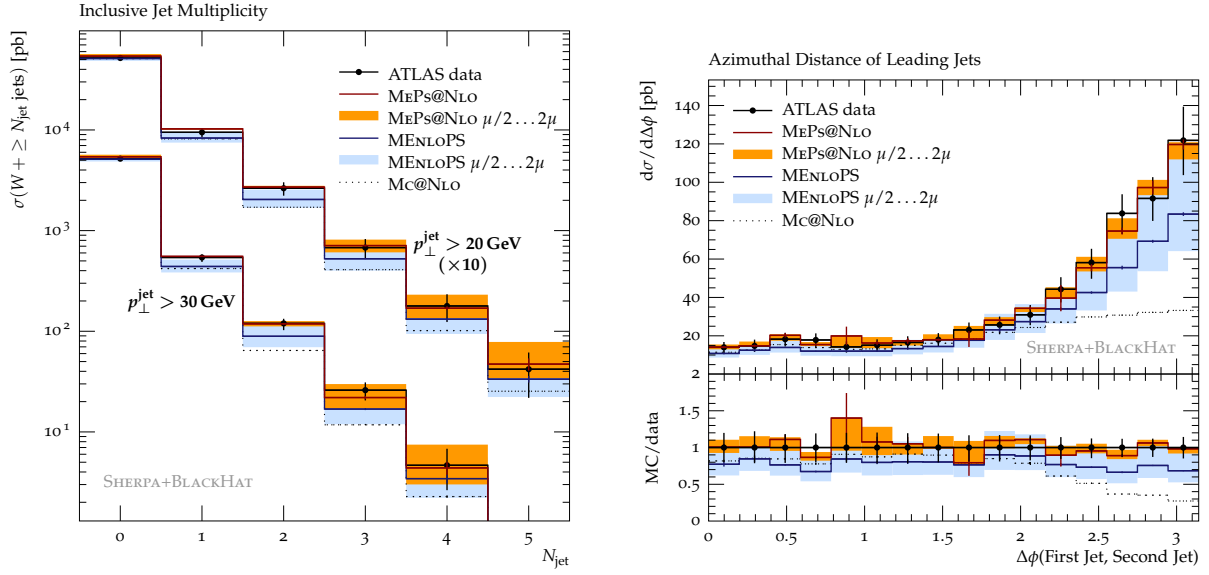**Figure 4:** $W+ \geq n$-jet cross sections **(left)** and azimuthal decorrelation of the two leading jets **(right)** in $pp \to W+$ jets production at the LHC compared to ATLAS data [11]. Figures taken from [35].

[10] Aad G *et al.* (ATLAS Collaboration) 2011 *Phys.Lett.* **B698** 325–345 (*Preprint* `1012.5382`)
[11] Aad G *et al.* (ATLAS Collaboration) 2012 *Phys.Rev.* **D85** 092002 (*Preprint* `1201.1276`) URL `http://inspirehep.net/record/1083318`
[12] Aad G *et al.* (ATLAS) 2012 *Phys.Rev.* **D85** 032009 (*Preprint* `1111.2690`) URL `http://inspirehep.net/record/945498`
[13] Chatrchyan S *et al.* (CMS) 2012 *JHEP* **1201** 010 (*Preprint* `1110.3226`) URL `http://inspirehep.net/record/940012`
[14] Chatrchyan S *et al.* (CMS Collaboration) 2013 (*Preprint* `1301.1646`)
[15] Campbell J M and Ellis R 2002 *Phys. Rev.* **D65** 113007 (*Preprint* `hep-ph/0202176`)
[16] Ellis R, Melnikov K and Zanderighi G 2009 *JHEP* **0904** 077 (*Preprint* `0901.4101`)
[17] Berger C F, Bern Z, Dixon L J, Febres-Cordero F, Forde D, Gleisberg T, Ita H, Kosower D A and Maître D 2009 *Phys. Rev. Lett.* **102** 222001 (*Preprint* `0902.2760`) URL `http://www.slac.stanford.edu/spires/find/hep/www?eprint=arXiv:0902.2760`
[18] Berger C F, Bern Z, Dixon L J, Febres-Cordero F, Forde D, Gleisberg T, Ita H, Kosower D A and Maître D 2011 *Phys. Rev. Lett.* **106** 092001 (*Preprint* `1009.2338`) URL `http://inspirebeta.net/record/867513`
[19] Berger C F, Bern Z, Dixon L J, Febres-Cordero F, Forde D, Gleisberg T, Ita H, Kosower D A and Maître D 2010 *Phys. Rev.* **D82** 074002 (*Preprint* `1004.1659`) URL `http://www-spires.dur.ac.uk/spires/find/hep/www?eprint=arXiv:1004.1659`
[20] Ita H, Bern Z, Dixon L J, Febres-Cordero F, Kosower D A and Maître D 2012 *Phys.Rev.* **D85** 031501 (*Preprint* `1108.2229`) URL `http://inspirehep.net/record/922868`
[21] Gleisberg T, Höche S, Krauss F, Schönherr M, Schumann S, Siegert F and Winter J 2009 *JHEP* **02** 007 (*Preprint* `0811.4622`) URL `http://inspirebeta.net/record/803708`
[22] Frixione S and Webber B R 2002 *JHEP* **06** 029 (*Preprint* `hep-ph/0204244`) URL `http://www.slac.stanford.edu/spires/find/hep/www?eprint=hep-ph/0204244`
[23] Frixione S, Nason P and Webber B R 2003 *JHEP* **08** 007 (*Preprint* `hep-ph/0305252`) URL `http://www.slac.stanford.edu/spires/find/hep/www?eprint=hep-ph/0305252`
[24] Höche S, Krauss F, Schönherr M and Siegert F 2012 *JHEP* **09** 049 (*Preprint* `1111.1220`) URL `http://inspirehep.net/record/944643`
[25] Nason P 2004 *JHEP* **11** 040 (*Preprint* `hep-ph/0409146`) URL `http://inspirebeta.net/record/659055`
[26] Frixione S, Nason P and Oleari C 2007 *JHEP* **11** 070 (*Preprint* `0709.2092`) URL `http://www.slac.stanford.edu/spires/find/hep/www?eprint=arXiv:0709.2092`
[27] Hamilton K, Richardson P and Tully J 2008 *JHEP* **10** 015 (*Preprint* `0806.0290`) URL `http://www.slac.stanford.edu/spires/find/hep/www?eprint=arXiv:0806.0290`
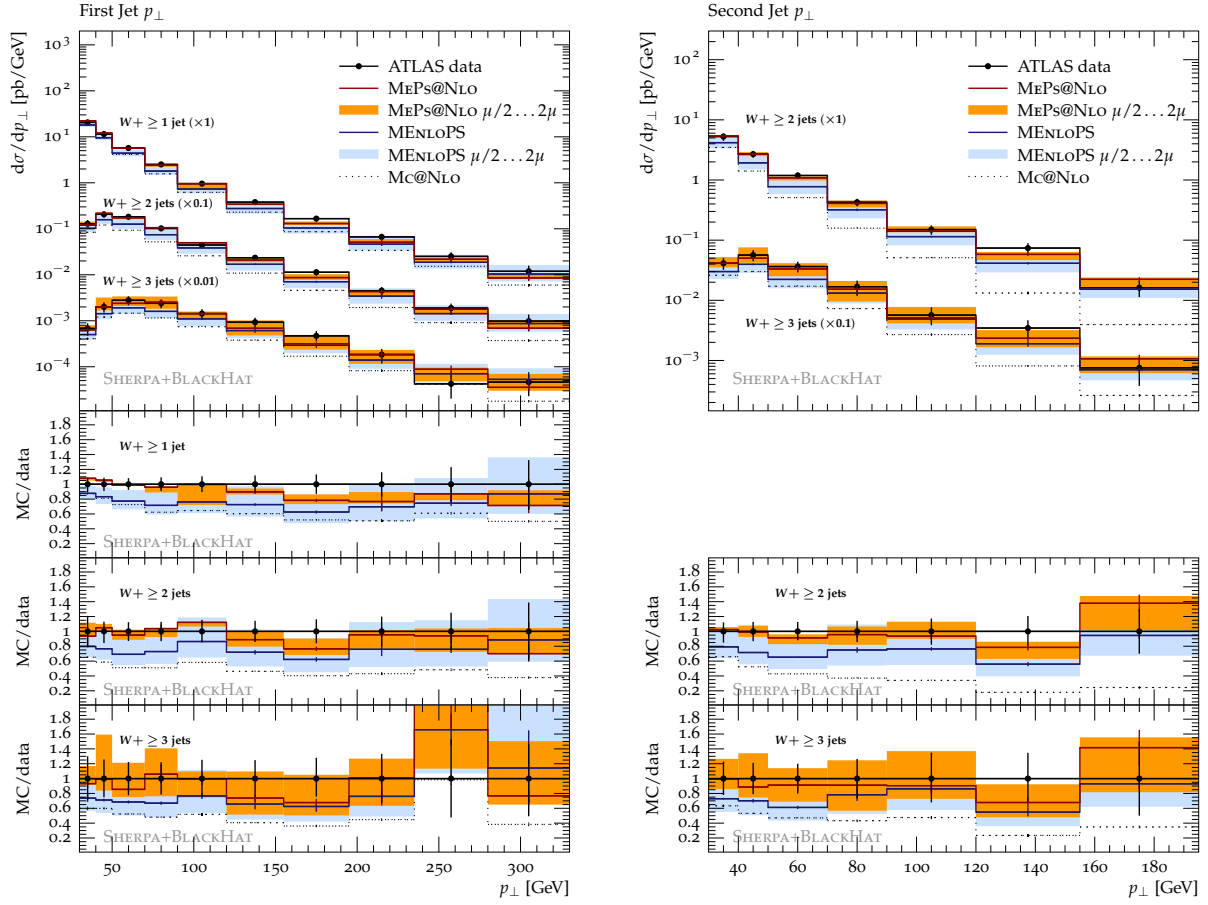
Figure 5: Transverse momentum of the leading and subleading jet in events with at least 1, 2 or 3 jets in $pp \to W+$ jets production at the LHC compare to ATLAS data [11]. Figures taken from [35].

[28] Höche S, Krauss F, Schönherr M and Siegert F 2011 *JHEP* **04** 024 (*Preprint* 1008.5399) URL http://inspirebeta.net/record/866705

[29] Höche S, Krauss F, Schönherr M and Siegert F 2013 *Phys.Rev.Lett.* **110** 052001 (*Preprint* 1201.5882) URL http://inspirehep.net/record/1086175

[30] Re E 2012 *JHEP* **1210** 031 (*Preprint* 1204.5433) URL http://inspirehep.net/record/1112186

[31] Frederix R, Frixione S, Hirschi V, Maltoni F, Pittau R *et al.* 2012 *JHEP* **1202** 048 (*Preprint* 1110.5502)

[32] Hamilton K and Nason P 2010 *JHEP* **06** 039 (*Preprint* 1004.1764) URL http://www.slac.stanford.edu/spires/find/hep/www?eprint=arXiv:1004.1764

[33] Höche S, Krauss F, Schönherr M and Siegert F 2011 *JHEP* **08** 123 (*Preprint* 1009.1127) URL http://www.slac.stanford.edu/spires/find/hep/www?eprint=arXiv:1009.1127

[34] Lavesson N and Lönnblad L 2008 *JHEP* **12** 070 (*Preprint* 0811.2912)

[35] Höche S, Krauss F, Schönherr M and Siegert F 2012 (*Preprint* 1207.5030) URL http://inspirehep.net/record/1123387

[36] Gehrmann T, Höche S, Krauss F, Schönherr M and Siegert F 2013 *JHEP* **1301** 144 (*Preprint* 1207.5031)

[37] Höche S and Schönherr M 2012 *Phys.Rev.* **D86** 094042 (*Preprint* 1208.2815) URL http://inspirehep.net/record/1127523